Rulemaking Committee dated April 6, 1993. The methods of the Final Majority Report have, in a sense, been somewhat refined in a paper published in August of 1993. (See "Coordination of Co-Coverage, Co-Frequency CDMA MSS Systems on the Basis of Impact on Capacity," Study Group WP 8D, Doc. No. USSG 8D-28, dated August 5, 1993) These two references, with the stronger reliance on the Final Majority Report, form the technical basis for the capacity predictions derived in this appendix.

The interference-sharing Constellation system uses four frequency channels each with a 2.56 MHz bandwidth within the 11.35 MHz provided for CDMA systems in the proposed L-band assignment plan. Therefore, each Constellation satellite must transmit 4 times more S-band power than in the baseline 2.56 MHz Constellation satellite design. To increase downlink capacity, the Constellation system can use two-satellite path diversity by either coherently combining two signals or use satellite selection and use the one satellite capable of providing the stronger signal. This may substantially increase the complexity of the subscriber unit receiver. Using satellite selection, beam or frequency-channel shut off may occur at some satellites to limit self-interference. The subscriber unit should be able to transmit to one or two satellites independently with a sufficiently high EIRP.

The downlink CONUS capacity is expected to be between 1200 and 1800 voice channels when sharing the band with three other systems, assuming system losses of 3 dB, a fixed margin of 3.5 dB, and provided alternating polarization isolation is used with an isolation factor of -4 dB. Without polarization isolation, the downlink capacity may be as low as 825 voice channels when sharing the 11.35 MHz band with three other strongly interfering systems.

The uplink capacity of the Constellation system may approximate 1700 to 2000 voice channels with the system losses, margin, and polarization isolation stated for the downlink.

Based on the analysis contained in this appendix, it is evident that the Constellation satellite design that is capable of satisfactory performance in the interference-sharing environment is substantially different than the simpler Constellation satellite design suitable for operating in a narrower band dedicated solely to its own use.

2. Description of Constellation's Current Baseline System

Constellation's current baseline design is capable of providing a minimum of 1,000 voice channels in a 2.56 MHz bandwidth using code division multiple access (CDMA) techniques at both L-band and S-band. This design conforms to all current sharing criteria, including the RR2566 power flux density limits, but assumes there is no other LEO system operating in the same 2.56 MHz band.

For the purpose of this analysis, Constellation has selected an orbital configuration consisting of 48 satellites, 8 satellites in 6 planes, inclined at approximately 52°, at an altitude of 2,000 km. With this orbital constellation, two or more satellites are visible over the continental United States (CONUS) with elevation angles of 25° for most of the time.

Each satellite has 10 antenna beams for connection to subscriber unit terminals at L-band and S-band. Constellation's baseline design utilizes fixed frequency FDMA feeder link operations where a fixed feeder link frequency is associated with a particular beam, but allows the transponder to be tuned to any discrete channel in the L-Band and S-Band service link bands. Table B-1 provides a reference link budget for this 2.56 MHz bandwidth baseline design.

The interference-sharing version of the Constellation system uses four frequencies (2.56 MHz bandwidth per frequency) per beam (instead of one as in the dedicated system) with a total bandwidth that fits easily within the allocated 11.35 MHz if it is all usable. The narrow per-channel bandwidth of 2.56 MHz is expected to facilitate tailoring the signals into the available 11.35 MHz band. The satellite L and S band antennas will still to the maximum extent possible within economic constraints use an isoflux antenna pattern with beams falling off as rapidly as the aperture permits outside their area of primary coverage.

The interference sharing satellites transmit a total of 4 times more S-band downlink RF power than in the 2.56 MHz dedicated case, which dramatically increases the size and weight of the satellites since S-band power is a major driver of satellite size and weight. The increased weight and size may create a major departure in launch configuration and introduce significant heat dissipation problems in the satellite design.

The interference-sharing Constellation system may use dual-satellite path diversity on the S-band downlink to take advantage of the -139 dBW/m^2-4kHz power flux spectral density limit per-system suggested in the Final Majority Report as opposed to the -142 dBW/m^2-4kHz limit applicable to a single satellite. Using the -139 dBW/m^2-4kHz limit allows the Constellation system to better tolerate the S-band downlink interference from the other systems, which apparently are considering transmitting from two satellites. Alternately, only one satellite at the highest elevation angle may be used, but the beam or 2.56 MHz frequency channel from the satellite with the next highest elevation angle which covers the same subscriber unit could be

Outbound Link Performance

Elevation Angle (°)	25	90
Range (km)	3368	2000
Uplink Frequency (MHz)	6558	6558
Transmit Power Per Carrier (watts)	0.2	0.2
Line Loss (dB)	0.5	0.5
TX Antenna Gain (dBi)	50.4	50.4
Transmit EIRP (dBW)	42.9	42.9
Misc. Uplink Losses (dB)	1.0	1.0
Path Loss (dB)	179.3	174.8
RX Antenna Gain (dBi)	3.0	3.0
Line Loss (dB)	0.5	0.5
RX Power Level (dBW)	-134.9	-130.4
Noise Density (dBW/Hz)	-202.6	-202.6
Uplink C/No (dB-Hz)	67.7	72.2
Downlink Frequency (MHz)	2492	2492
Power per carrier (dBW)	-3.9	-7.1
Line Loss (dB)	1.5	1.5
TX Antenna Gain (dBi)	15.9	14.6
Carrier EIRP (dBW)	10.5	6.0
Miscellaneous Downlink Losses (dB)	0.5	0.5
Path Loss (dB)	170.9	166.4
Power Flux Density (dBW/m^2-4kHz)	-142.0	-142.0
RX Antenna Gain (dBi)	3.0	3.5
Line Loss (dB)	0.5	0.5
RX Power Level (dBW)	-158.4	-157.9
Noise Density (dBW/Hz)	-203.5	-203.5
Downlink C/No (dB-Hz)	45.0	45.6
Code and Adj Beam Noise Factor (numerical)	0.21	0.21
Code Noise Density @ User (dBW/Hz)	-205.5	-205.0
Code Noise C/Io (dB-Hz)	53.9	53.9
Link C/No (dB-Hz)	44.5	45.0
Eb/No (dB)	7.5	8.0
Matched Filter Loss (dB)	1.0	1.0
Demodulator Implementation Loss (dB)	0.25	0.25
Required Eb/No (dB)	2.8	2.8
Margin (dB)	3.5	3.9

Inbound Link Performance

Elevation Angle (°)	25	90
Range (km)	3368	2000
Uplink Frequency (MHz)	1618	1618
Transmit Power Per Carrier (mw)	600.0	250.0
Line Loss (dB)	0.5	0.5
TX Antenna Gain (dBi)	3.0	3.5
Transmit EIRP (dBW)	0.3	-3.0
Misc. Uplink Losses (dB)	0.5	0.5
Path Loss (dB)	167.2	162.7
RX Antenna Gain (dBi)	15.5	14.6
Line Loss (dB)	1.0	1.0
RX Power Level (dBW)	-152.9	-152.6
Noise Density (dBW/Hz)	-202.6	-202.6
Uplink C/No (dB-Hz)	49.7	50.0
Downlink Frequency (MHz)	5183	5183
Power Per Carrier (dBW)	-16.5	-16.5
Line Loss (dB)	0.5	0.5
TX Antenna Gain (dBi)	3.0	3.0
EIRP Per Carrier (dBW)	-14.0	-14.0
Miscellaneous Downlink Losses (dB)	1.0	1.0
Path Loss (dB)	177.3	172.8
Power Flux Density (dBW/m^2-4kHz)	-166.5	-161.9
RX Antenna Gain (dBi)	48.4	48.4
Line Loss (dB)	0.5	0.5
RX Power Level (dBW)	-144.3	-139.8
Noise Density (dBW/Hz)	-204.1	-204.1
Downlink C/No (dB-Hz)	59.7	64.2
Code and Adj Beam Noise Factor (numerical)	1.21	1.21
Code Noise Density @ Satellite (dBW/Hz)	-200.0	-199.6
Code Noise C/Io (dB-Hz)	46.2	46.2
Link C/No (dB-Hz)	44.5	44.7
Eb/No (dB)	7.5	7.7
Matched Filter Loss (dB)	1.0	1.0
Demodulator Implementation Loss (dB)	0.25	0.25
Required Eb/No (dB)	2.8	2.8
Margin (dB)	3.5	3.6

Table B-1. Baseline 2.56 MHz Bandwidth Constellation Link Budget

turned off by the system controller to limit self-system interference. With two satellites available at relatively high elevation angles, i.e. above 25°, very likely the one satellite selected for transmission will have a strong signal and reduced impairments.

The baseline Constellation system uses time synchronization of codes on the outbound link to the subscriber units to minimize self-interference. However, as other systems deploy and share the band this expensive synchronization provides less significant gains in capacity beyond what would be achieved without any synchronization. Hence, time synchronization may not be as cost effective in the interference-sharing environment.

As suggested in the Final Majority Report, to reduce interference among systems, the use of alternating right hand and left hand circular polarization should be required as systems deploy. This interference-mitigating procedure is assumed in the analyses of this appendix.

Constellation's subscriber units are assumed to have at least a dual channel receiver capable of acquiring and tracking two satellites (and their associated pilot/control beacons) independently and either coherently combining the received messages or causing the satellite capable of providing the stronger signal to be selected by the system controller for transmission. The transmitter may need to transmit independently on two channels with a sufficiently high EIRP per channel. (RR 731F would permit up to a 20 watt transmission corresponding to the EIRP density limit of -15 dBW/4 kHz within the 2.56 MHz bandwidth per frequency/channel). The maximum antenna gain of about 3.5 dB means that the subscriber unit amplifier must deliver up to about 9 watts per channel when the link is obstructed, compared to a nominal value of less than 1 watt when the satellite path is unobstructed. The high peak transmitted power allows the Constellation system to better withstand the potentially more numerous, but lower powered, handheld units of the other systems. The higher power available provides headroom potentially needed to close links with high impairments such as foliage and some structure losses.

The subscriber unit dual band antenna is also assumed to have a maximum gain at zenith of about 3.5 dB with a 3 dB beamwidth of about 110° with a gain of -3 dB or less at 10° elevation to allow an antenna temperature of about 130K.

3. Measures of System Capacity

The link budget for Constellation's baseline or 2.56 MHz dedicated system indicates the system capacity available in the absence of interference from any other satellite system. Under the CDMA interference sharing approach described in the Final Majority Report, it is necessary for the Constellation system to transmit over a wider bandwidth and with more total power to overcome the effects of intersystem interference and maintain the same system capacity that was available in the absence of inter-system interference. To compare alternatives, it is necessary to derive a general system capacity model for the CDMA interference sharing environment.

The methods used in the Final Majority Report derive system capacity in three steps. In each step, the capacity is expressed in terms of simultaneous two-way conversations for a CONUS system. Following the steps, increasingly more realistic estimates of system capacity are derived. Only, the result of the third step, which accounts for margin and all sources of interference, should be interpreted as an estimate of the capacity actually achievable in practice.

While closely following the Final Majority Report approach, this analysis first calculates the capacity in terms of voice channels or two-way conversations per beam per 2.56 MHz channel. This result is then extended to the CONUS coverage provided by a single Constellation satellite by multiplying the capacity per frequency channel by the 4 frequencies used per beam times the 10 beams per satellite. That is, the number of CONUS conversations or voice channels is 40 times the capacity in voice channels per beam per 2.56 MHz.

It should be emphasized, that the increased size, weight, and power of the satellites needed in the interference-sharing Constellation system and their associated launch costs combined with the increased complexity and power of the subscriber unit equipment may produce a significant change in revenue requirements for this case compared to dedicated narrower band Constellation system.

4. Capacity Predictions

The outbound (S-band) and inbound (L-band) capacity predictions derived below are intended to both estimate the Constellation system capacity and identify the changes in the system relative to the narrower band dedicated Constellation satellites needed to achieve that capacity.

4.1 Outbound S-Band Downlink Capacity Predictions

This section is divided into two parts. Section 4.1.1 summarizes the mathematical basis for calculation of the S-band downlink capacity. This section is needed because there are certain assumptions made in the analysis of the Final Majority Report which are not obvious unless they are compared to a detailed analysis. Section 4.1.2 calculates the capacity using the formulas derived in section 4.1.1 which verify the conditions in which the estimates following the methods of the Final Majority Report give accurate capacity estimates.

4.1.1 Mathematical Basis for Outbound Downlink Capacity Analysis

The power received from each of two transmitting satellites at a given subscriber unit S-band receiver assuming ideal free space propagation is given by

$$S_i = [P_{ti}G_{tir}/4\pi D_i^2]\ [1/M_i]\ [G_{rti}\lambda_i^2/4\pi]\ [1/L_{fl}L_r L_{ds}L_{dem}] \tag{1}$$

where the subscript i, i=1, 2 indexes the two transmitting satellites and most of the symbolism is common with P_{ti} being the total transmit power of the ith satellite which when divided by the number of downlinks M_i yields the average downlink power per circuit. The losses denoted by L_{fl}, L_r, L_{ds}, and L_{dem} are the receiver feeder-link losses, receiver losses up to the matched filter or correlator despreader, L_{ds} is the loss in the despreader, and L_{dem} is the demodulator loss or offset from ideal demodulator performance.

The term $[P_{ti}G_{tir}/4\pi D_i^2]$ is assumed to be held equal to its maximum allowed value of $PFSD_{max}W_{DS}$, where PFSDmax is the maximum allowed power flux spectral density assumed equal to -142 dBW/m^2-4kHz or -178 dBW/m^2-Hz (for elevation angles of 25° or more) and W_{DS} is the transmitted direct sequence bandwidth equal to 2.56 MHz in the interference-sharing Constellation system. Hence, while potentially different for each transmitting satellite, the term $[P_{ti}G_{tir}/4\pi D_i^2]$ is assumed equal to $PFSD_{max}W_{DS}$ or -113.9

dBW/m^2 at the subscriber unit for both satellites if both are viewed at elevation angles of at least 25°.

The term $[G_{rti}\lambda_i^2/4\pi]$ is the effective area of the subscriber unit receive antenna which at a frequency of 2500 MHz has a wavelength of 0.12 meters which at a gain of 3.5 dB (2.24) yields an effective area of -25.9 dBm^2. Since the gains may be different for the two satellites, the effective areas may not be the same.

The subscriber unit may function in either of two ways. One, it may communicate the received power over control channels and cause the system controller to select the one satellite with the stronger signal. In this case, the system controller turns off the power in at least the one beam or frequency channel used by the desired subscriber unit from the satellite at the next highest elevation angle which would otherwise produce significant self interference. Alternately, the subscriber unit receiver can combine the signals from the two transmitting satellites coherently and thus increase the signal-power-to-interference-power ratio by about 3 dB.

In this analysis, the subscriber unit is assumed to cause the selection of one transmitting satellite capable of providing the strongest signal. The system avoids the strongest self-interference from our own satellites at high elevations angles by turning off the power in at least one beam or frequency channel.

The power S of the stronger signal at the subscriber unit receiver is equal to

$$S = PFSD_{max}\, W_{DS}\, A_e\, [1/M]\, [1/L_{fl}L_rL_{ds}L_{dem}] \qquad (2)$$

where $PFSD_{max}$ is equal to -142 dBW/m^2-4kHz assuming the satellite is at an elevation angle of at least 25°, M is the number of signals instantaneously sharing the in satellite transmitted power, and A_e is the effective area of the receive antenna at maximum gain. With S equal to $E_b R_b$, where E_b is the energy per and R_b is the bit rate, E_b equals S/R_b and the energy per bit equals

$$E_b = PFSD_{max} W_{DS} A_e [1/M] [1/L_{fl} L_r L_{ds} L_{dem}] [1/R_b] \qquad (3)$$

If the only source of receiver degradation were receiver thermal noise with noise power spectral density of N_o Watts/Hz, Eq. (3) could be divided by N_o yielding E_b/N_o equal to

$$E_b/N_o = PFSD_{max} W_{DS} A_e [1/M] [1/L_{fl} L_r L_{ds} L_{dem}] [1/N_o R_b] \qquad (4)$$

which in turn could be solved for the number of users M yielding

$$M = PFSD_{max} W_{DS} A_e [1/(E_b/N_o)] [1/L_{fl} L_r L_{ds} L_{dem}] [1/N_o R_b] \qquad (5)$$

Setting $(E_b/N_o) L_{fl} L_r L_{ds} L_{dem}$ equal to its minimum value needed to achieve the desired bit error rate after correction by the Error Detection and Correction (EDAC) or Forward Error Correction (FEC) coding, denoted by $(E_b/N_o)_{min}$, the maximum capacity of the downlink under the ideal conditions reflected by Eq. (5), denoted by M_{mid}, equals

$$M_{mid} = PFSD_{max} W_{DS} A_e [1/(E_b/N_o)_{min}] [1/h_v N_o R_b] \qquad (6)$$

where the voice activity factor denoted by h_v is assumed to equal 1/2.

However, the capacity predictions using Eq. (6) are certainly an upper bound based on ideal circumstances. A more reasonable capacity value may be obtained by accounting for a number of randomly occurring factors which typically decrease the power of the desired signal. These random occurrences are compensated for using a fixed link margin. These margin factors include the following:

- margin for propagation impairments due to non-ideal free-space paths;
- margin for variations in Gtr/D^2 which account for the inability to build a perfect isoflux satellite transmit antenna; and
- margin for average variation from perfect power control.

Taking all these random-signal losses into account by the total margin factor L_m, a refined measure of link capacity called the maximum realizable downlink capacity, denoted by M_{mrd}, is given by

$$M_{mrd} = M_{mid}/L_m \qquad (7)$$

where the value of L_m equals several dB.

A fourth factor called beam spillover or overlap margin equal to the average of power from the intended beam at the subscriber unit plus power from other beams divided by the power in the intended beam alone was introduced by the Final Majority Report. However, it seems more appropriate to account for this factor during the analysis of the interference issues which are discussed next.

The final, and the most complex, issue is the effect of interference on the capacity of the downlink. This interference is caused by the Constellation system to itself, in which case it is called background and denoted by B_o and expressed in units of Watts/Hz or dBW/Hz. Interference is also caused by the other systems which share the 11.35 MHz with the Constellation system. This interference spectral density is denoted by I_O and has the same units as B_O.

At least on a preliminary basis it seems convenient to identify the following sources of power which contribute to B_O at a given desired subscriber unit:

a. power transmitted to other Constellation subscriber units in the same mainbeam as the desired one and received by the desired subscriber unit at mainbeam antenna gain;

b. power transmitted to other Constellation subscriber units in beams which are adjacent to the mainbeam, containing the desired subscriber unit, which reaches the desired subscriber unit via sidelobes or low antenna gains; and

c. power transmitted in other beams of the Constellation system which, while intended for other subscriber units, arrives at the desired subscriber unit via transmit antenna sidelobes or low antenna gains.

Sources of power listed in categories a. and b. above are denoted respectively by B_{Oa} and B_{Ob} and are assumed to come from the same satellite servicing the desired subscriber unit. Source c. in the list above, denoted by B_{Oc}, is assumed to come from all other Constellation satellites in view from the desired subscriber unit. In this connection, the subscriber unit receive antenna is assumed to fall off rapidly at elevation angles below about 10-15° to limit interference from all satellites near the horizon and to lower the antenna temperature of the subscriber unit antenna. The total background or own-system or self-interference B_O equals $B_{Oa}+B_{Ob}+B_{Oc}$ with units of Watts/Hz.

In this analysis, the power contained in signals to other subscriber units in the mainbeam with the desired subscriber unit, denoted by B_{oa}, is diminished by an orthogonality factor α equal to .1 by using orthogonal Walsh codes and synchronizing the transmissions in each beam to a fraction of the chip interval. Furthermore, the power in the beam from at least one other Constellation satellite at high elevation angle with high gain at the desired subscriber unit is assumed to be turned off to minimize self interference B_{oa}. Alternately, the subscriber unit may combine signals from the two Constellation satellites at the highest elevation angles; but, the lower self-interference option is assumed in this analysis.

Sources of interference from other systems with which the Constellation system shares its spectrum are categorized similarly to the way B_o is above. Namely, the sources of power which contribute to Io include the following:

a. power received at a Constellation system desired subscriber unit while in the mainbeam of another satellite; e.g., the desired subscriber unit in the Constellation system is in the beam of a satellite belonging to another system which would be used by that system to transmit to the Constellation system subscriber unit if the Constellation subscriber unit belonged to that system. (The Constellation system subscriber unit is in the footprint of maximum gain of a beam from another system);

b. power received at a Constellation desired subscriber unit while in beams which neighbor the mainbeam of another satellite; e.g., the desired subscriber unit in the Constellation system is in a beam of a satellite belonging to another system which neighbors (or is adjacent to) the beam which would be used by that system to transmit to a Constellation subscriber unit if the Constellation subscriber unit belonged to that system. (The Constellation subscriber unit is in the footprint of a beam adjacent to the mainbeam from another system) ; and

c. power received at a Constellation desired subscriber unit while in other beams from satellites belonging to another system.

The three contributors to I_o from the ith interfering other system are denoted by I_{oai}, I_{obi}, and I_{oci}. The total interference power density at the Constellation subscriber unit from the ith interfering system is denoted by I_{oi} and equals $I_{oai}+I_{obi}+I_{oci}$ Watts/Hz. When there are N_s other interfering systems, the total interference power density from these other systems equals $\Sigma \beta_i I_{oi}$ Watts/Hz, where the summation is over the N_s interfering systems and β_i is a polarization isolation factor assumed equal to -4 dB or a factor of .4 when polarization is different and unity when it is the same.

Using the notation defined above, the ratio of energy per bit to all the sources of noise-like interfering power spectral density similar to Eq. (4), which accounted for thermal noise only, is given by

$$E_b/(N_o+B_o+\Sigma \beta_i I_{oi}) = E_b/(N_o+B_o+I_o) = \tag{8}$$

$$PFSD_{max}\, W_{DS}\, A_e\, [1/M]\, [1/L_m L_{fl} L_r L_{ds} L_{dem}][1/(N_o+B_o+I_o)R_b]$$

which by the inclusion of the margin term L_m accounts for a number of the principal uncertainties in the link power budget. Denoting $N_o+B_o+I_o$ by N_{oT}, Eq. (8) can be written in the form

$$E_b/N_{oT} = PFSD_{max}\, W_{DS}\, A_e\, [1/M]\, [1/L_m L_{fl} L_r L_{ds} L_{dem}][1/N_{oT} R_b] \tag{9}$$

What is very apparent from Table B-2 is the very substantial reduction in capacity when even the first sharing system is deployed. This is a fundamental problem which is not meaningfully changed even if the maximum allowed power flux spectral density is increased well above the current limit of -142 $dBW/m^2$4-kHz. The Final Majority Report is somewhat misleading in this respect because it references its interference power of other systems to the thermal noise power. But in any reasonable operation, the system power will be scaled according to the maximum power flux spectral density allowed. When this happens, the realizable capacity increases slowly with increases in the maximum satellite transmitted power. Indeed it may well be the case that the weight of the satellite and perhaps its overall cost increases with satellite S-band power faster than the capacity increases.

The capacity predictions of Table B-2 assumed that two satellites from each other system were in view from the desired Constellation subscriber unit at elevation angles of 25° or more. This results in interference which is stronger than expected since the Odyssey system using a high orbit is expected to have only one satellite in view at a high elevation angle and the other two systems (Globalstar and Ellipsat) plan to use elevation angles well below 25°. Therefore, the expected interference levels and the resulting Constellation system downlink capacity are more likely to be as follows. The Odyssey system is assumed to have one satellite in view yielding 3 dB lower I_{oai} than assumed in the first case. Hence, I_{oai} for Odyssey equals -205.4 dBW/Hz or 2.884×10^{-21} W/Hz. Odyssey uses about 19 beams so there are 18 adjacent beams assumed to be -20 dB down from the mainbeam on the average yielding I_{obi} equal to $(18/100)I_{oai}$ or 5.191×10^{-22} W/Hz. All other beams are assumed to contribute $I_{oai}/100$ or -225.4 dBW/Hz or 2.884×10^{-23} W/Hz. The total I_{oi} for the Odyssey system is therefore 3.432×10^{-21} W/Hz. For Odyssey, I_{oi}/N_o equals .882 meaning that the Odyssey system could contribute to Constellation system interference at a level somewhat less than Constellation's own thermal noise. The use of polarization isolation will further reduce this source of interference.

The other two systems are assumed to have two satellites in view from a Constellation subscriber unit, but at elevation angles which average 20° instead of 25° or more. In this case, the average allowed PFSD limit is decreased 2.5 dB from -142 dBW/m^2-4kHz to -144.5 dBW/m^2-4kHz. Hence, the power from each satellite is 2.5 dB below the -205.4 dBW/Hz level calculated in Eq. (24) bringing the I_{oai} for each of the other systems to -205.4 -2.5 +3 or -204.9 dBW/Hz or 3.236×10^{-21} W/Hz. The other contributions, I_{obi} and I_{oci}, are assumed to be $I_{oai}/10$ and $I_{oai}/100$ respectively yielding an I_{oi} for each of the other two systems of $1.11 \times 3.236 \times 10^{-21}$ or 3.592×10^{-21} W/Hz. For these two systems I_{oi}/N_o equals .923 meaning that each of these systems could interfere with Constellation system somewhat less that the interference caused by Constellation's own thermal noise.

The denominator $[1+(B_o/N_o)+\Sigma \beta_i I_{oi}/N_o)]$ in Eq. (27) can now be recalculated. Various combinations of β_i and I_{oi} are possible. Assume that the Constellation system deploys second yielding β_1, β_2, β_3 equal to .4, .4, 1 respectively. Suppose that the order of systems deployed is either Globalstar or Ellipsat, then the Constellation system, then Odyssey, then Globalstar or Ellipsat whichever didn't deploy first. With this ordering, the CONUS capacity of the Constellation system is as shown in Table B-3.

Table B-3, based on more realistic estimates of the inter-system interference, suggests that the realizable downlink capacity may approach 1800 voice channels with the losses, fixed margin, and polarization isolation factors assumed in this analysis.

Other System	CONUS Capacity (Voice Channels)
Globalstar or Ellipsat	3,300
Odyssey	2,680
Ellipsat or Globalstar	1,797

Table B-3. Predicted Maximum Realizable S-Band Downlink Capacity (Expected Interference with Polarization Isolation)

The last remaining issue is to compare the estimates of realizable downlink capacity based on the analysis of section 4.1.1 with the corresponding prediction of the realizable downlink capacity in the Final Majority Report, which is denoted by C_{RD}. From Eqs. (7) and (20), the realizable capacity equals

$$M_{rd} = M_{mrd}\ [N_o/(N_o+B_o+\Sigma ß_i I_{oi})] = [M_{mid}/L_m]\ [N_o/(N_o+B_o+\Sigma ß_i I_{oi})] \quad (28)$$

and from Eqs. (17) and (18)

$$M_{rd} = C_{MRD}\ [PFSD_{max}\ A_e/N_o]\ [N_o/(N_o+B_o+\Sigma ß_i I_{oi})] \quad (29)$$

$$= C_{MRD}\ [PFSD_{max}]\ [A_e/(N_o+B_o+\Sigma ß_i I_{oi})]$$

From Eq. (24), if the value of B_o were dominated by the B_{oa} mainbeam contribution, then neglecting the loss term L_r, B_o/A_e is approximately equal to B_{oa}/A_e which equals $PFSD_{max}$. Then Eq. (29) becomes

$$M_{rd} \approx C_{MRD}\ [PFSD_{max}]/[(N_o/A_e)+PFSD_{max}+\Sigma(ß_i I_{oi}/A_e)] \quad (30)$$

Defining $PFSD_{max}$ as r_{sd}, N_o/A_e as r_{nd}, and I_{oi}/A_e as r_{id}, Eq. (30) can be written in the form

$$M_{rd} \approx C_{MRD} \left[r_{sd}/(r_{nd} + r_{sd} + \Sigma \beta_i r_{id})\right] \tag{31}$$

which is equivalent to the expression used in the Final Majority Report for the realizable downlink capacity, denoted by C_{RD}, when the use of orthogonal codes is not accounted for. Hence, except for the loss factor L_r and the potential difference between C_{MID} and M_{mid}, the results of section 4.1.1 agree with the formulas for realizable capacity in the Final Majority Report. There are differences in the application and values used in these formulas with the biggest difference apparently being the orthogonality of much of the Constellation system's self interference. In fact, the Final Majority Report compensates for the losses introduced in section 4.1.1 by having larger margins than assumed in this report.

The capacity of the Constellation system is limited by the smaller of the downlink or uplink capacities. The next section of this report addresses the capacity of the L-band uplink of the interference-sharing Constellation system.

4.2 Inbound L-Band Uplink Capacity Predictions

The capacity on the inbound L-band uplink is conceptually more straight forward than the capacity of the downlink, but it is more difficult to accurately estimate because the power radiated from satellites is easier to estimate than the power radiated from subscriber units both in terms of EIRP and the number of such emitters. The inbound uplink capacity prediction is based on calculating the signal to noise-plus-interference ratio on the uplink at the input to the satellite relay amplifier. At the amplifier, the inputs include the desired subscriber unit signal power, the power from all the other subscriber units in the Constellation system which interfere with the desired signal, the thermal noise introduced by the satellite front end, and the power from all the other subscriber units in other systems. The capacity of the uplink occurs when the ratio of the desired signal power to the sum of the powers from the other three sources reaches a critically small value determined by the E_b/N_o required at the gateway receiver to achieve the required system bit error rate.

Following the outline of section 4.1, section 4.2.1 develops the mathematical basis for the capacity predictions and section 4.2.2 applies the prediction formulas to the Constellation system and compares the results to those obtained in the Final Majority Report.

4.2.1 <u>Mathematical Basis for Inbound Uplink Capacity Analysis</u>

The power received from the desired subscriber unit transmitter at the amplifier in the ith Constellation satellite equals

$$S_i = [P_t G_{tri}/4\pi D_i^2]\,[G_{rit}\lambda_i^2/4\pi]\,[1/L_s] \tag{32}$$

where i equal to 1 and 2 indexes the two satellites which could efficiently transmit to the subscriber unit and which could also relay messages from the subscriber unit to the gateways. L_s is the loss in the satellite from the receive antenna to the relay amplifier. To simplify the gateway equipment and inter-gateway communications, the gateways are assumed to process the signals from the two satellites and, under system control, use only the larger of the two to route the message to the user. The power S of the stronger of the two desired signals is then given by

$$S = [P_tG_{tr}/4\pi D^2]\,[G_{rt}l^2/4\pi]\,[1/L_s] = [P_tG_{tr}/L_s]\,[G_{rt}/4\pi D^2]\,[\lambda^2/4\pi] \qquad (33)$$

The energy per bit E_b in the power input to the relay amplifier is given by S/R_b and therefore, using Eq. (33), equals

$$E_b = [P_tG_{tr}/L_s]\,[G_{rt}/4\pi D^2]\,[\lambda^2/4\pi]\,[1/R_b] \qquad (34)$$

There are M other Constellation system subscriber units in the same satellite mainbeam as the desired subscriber unit which are also being relayed to some gateway on nearly the same frequency. The E_b for each of these other bonafide signals is expected to equal the E_b for the desired signal. Hence, the total input power at the relay amplifier in these M signals equals MS. The self-interference PSD, B_o, generated by these other signals is given by

$$B_o = MS/W_{DS} \qquad (35)$$

The satellite introduces thermal noise with a noise PSD equal to N_o Watts/Hz. Initially ignoring the effects of the power from other systems, the ratio of desired bit energy E_b to undesired PSD N_o+B_o equals

$$E_b/(N_o+B_o) = [S/R_b]/[N_o+(MS/W_{DS})] \qquad (36)$$

Solving Eq. (36) for M, the number of other subscriber units in the mainbeam yields

$$M = [W_{DS}/R_b]/[(E_b/(N_o+B_o)] - [N_o W_{DS}/S] \tag{37}$$

Setting the ratio $E_b/(N_o+B_o)$ equal to its minimum value $(E_b/(N_o+B_o)_{min}$ needed to achieve the required bit error rate defines the maximum ideal uplink capacity M_{miu} equal to

$$Mmiu = \{[W_{DS}/R_b]/[h_v(E_b/(N_o+B_o)_{min}]\}- [N_o W_{DS}/h_v S] \tag{38}$$

when the voice activity factor h_v equal to 1/2 is included. Since S equals $E_b R_b$, Eq. (38) may be rewritten in the forms

$$M_{miu} = \{[W_{DS}/h_v R_b]/[(E_b/(N_o+B_o)_{min}]\}- [(W_{DS}/R_b)/h_v(E_b/N_o)] \tag{39a}$$

$$= [W_{DS}/h_v R_b]/[1/(E_b/(No+B_o)_{min}-1/(E_b/N_o)] \tag{39b}$$

The ratio E_b/N_o is expected to be much larger than $(E_b/(N_o+B_o)_{min}$ to allow B_o to be much larger than No. Using Eq. (34) assume that the subscriber unit EIRP is 3.5 dBW, the satellite loss is 1 dB, the path attenuation is 167.5 dB at 1615 MHz for a communications distance of 3500 km an the edge of coverage, the gain of the satellite antenna is approximately 15 dB, and the transmitted bit rate is 5 kbits/sec or (37 dBbits/sec). Then E_b equals about -187 dBW/Hz. With a satellite system temperature of 400 K, the noise PSD equals -202.6 dBW/Hz and E_b/N_o equals 15.6 dB. This ratio can be raised by as much as 16.5 dB and not exceed the EIRP limit of -15 dBW/4kHz. Since $E_b/(N_o+B_o)_{min}$ is just a few dB, the E_b/N_o term in Eq. (39) is negligible and the final expression for the maximum ideal uplink capacity becomes

$$M_{miu} = [W_{DS}/h_v R_b]/[(E_b/(N_o+B_o)_{min}] \tag{40}$$

Equation (40) used here to define M_{miu} is used in the Final Majority Report to define the maximum ideal uplink capacity denoted there by the symbol C_{MIU}. Hence, since E_b/N_o will be much larger than $E_b/(N_o+B_o)_{min}$

$$M_{miu} = C_{MIU} \tag{41}$$

As in the downlink analysis in section 4.1.1, the maximum realizable uplink capacity must take several random system uncertainties into account by providing a link margin. The sources considered in the Final Majority Report were identified in section 4.1.1. Denoting the total margin by L_m, the maximum realizable uplink capacity, M_{mru}, is given by

$$M_{mru} = M_{miu}/L_m = C_{MIU}/L_m \tag{42a}$$

$$= C_{MRU} \tag{42b}$$

The term C_{MIU}/L_m in Eq. (42a) is called the maximum realizable uplink capacity in the Final Majority Report and denoted by C_{MRU}. Then, M_{mru} equals C_{MRU} as in Eq. (42b).

As in section 4.1.1, the third step in estimating the uplink capacity is to account for the interference at the satellite caused by power transmitted by subscriber units not in the mainbeam footprint with the desired subscriber unit and power transmitted from subscriber units belonging to other systems. The impact of these sources of interference on the uplink capacity will be considered next.

Following the development for the background PSD B_o and interference PSD I_o used in section 4.1.1, the background term B_{oa} from other Constellation subscriber units in the mainbeam has already been accounted for in the calculation of maximum ideal and maximum realizable capacities above. The two other sources of self-interference or background from the Constellation system include other subscriber units in the footprints of beams adjacent to the mainbeam containing the desired subscriber unit and subscriber units in all the footprints of all remaining beams on the satellite which is relaying the stronger desired signal to a gateway. Accurately estimating the level of power from these two sources is not easy.

If the interference-sharing Constellation system were to use beams with a "rectangular" footprint, only the subscriber units in the footprints of the two beams (typically) immediately adjacent to the mainbeam make any significant contribution to the background. This follows since the gain in the direction of non-adjacent footprints is expected to be down 30 dB or more. The gain is typically 20 dB down in adjacent beams. The subscriber units in each immediately adjacent beam are assumed to average 10 dB below the desired signal. This is estimated as follows. N_{in} subscriber units are assumed to be in the edge of the mainbeam and in an adjacent beam. The power from these subscriber units equals S, the same as from the desired subscriber unit. N_{out} subscriber units are in the adjacent beam but out of the mainbeam high-gain footprint. The power from these subscriber units is assumed to be 20 dB down on the average. Under these assumptions, the received power from one adjacent beam equals $N_{in}S+N_{out}S/100$. With N_{in} equal to 10% of the beam capacity M, the beam power equals .109SM. The corresponding contribution to the background PSD equals .109SM/W_{DS}, which is essentially 10 dB below the mainbeam background Boa equal to SM/W_{DS}. Two such beams exists, except on the two outside beams, and B_{ob} is therefore typically equal to $B_{oa}/5$.

Since the other subscriber units contributing to B_{oc} are received with gains some 30 dB below the mainlobe gain, they make no significant contribution to the back-ground. Therefore, B_{oc} is negligibly small and is set equal to zero. In summary, the background B_o equals $B_{oa}+B_{oa}/5$ or 1.2 B_{oa}.

The remaining, and most problematical, source of interference is the power from subscriber units belonging to other systems. The numbers of the subscriber units for the other systems is one uncertainty. Another key uncertainty is the type of subscriber unit deployed by the other companies. More to the point, what types of subscriber units will the using public buy and it what numbers? Also how will the services and their associated subscriber units be distributed across the country?

As a baseline, all other systems will be referenced to the Constellation system. Following the approach of section 4.1.1 for the downlink, the interference I_{oai} from other subscriber units belonging to another system in the footprint of the mainbeam containing the desired subscriber unit in the Constellation system would equal B_{oa} if the other system were just like the Constellation system. But it probably won't be. Particularly important is the goal of some other systems to emphasize handheld units capable of direct transmission to their satellite repeaters. The EIRP from these handheld units may be limited to well less than a Watt compared to up to 20 Watts allowed for the Constellation system based on the RR 731F limit of -15 dBW/4kHz. However, the CONUS market may favor handheld units as opposed to the more pragmatic basic communications needs of a settlement or individual in a remote area not served by terrestrial communications. Not withstanding the uncertainties involved, I_{oai} is assumed to equal

$$I_{oai} = [F_{ci}F_{pi}/F_{bi}]\, B_{oa} \tag{43}$$

where F_{ci} is the capacity or number of subscriber units of the ith system in the footprint of the mainbeam relative to (divided by) the number of subscriber units in the mainbeam belonging to the Constellation system. F_{pi} is the average power other the subscriber units in the other system compared to (divided by) the power of the Constellation system. The factor F_{bi} is the ratio of the bandwidth of the ith system relative to (divided by) the 2.56 MHz bandwidth of the Constellation system. In some cases, increases in the power factor F_{pi} may be offset by proportionately larger F_{bi} factors.

As estimated earlier for B_{ob}, I_{obi} is set equal to $I_{oai}/5$. This is critically dependent on the rate at which the gain of the satellite antenna beams fall off outside the region in which they are used to synthesize the combined iso-flux pattern. Following the reasoning used to set B_{oc} equal to zero, I_{oci} is also set equal to zero. Then the total PSD equal to $N_o+B_o+\Sigma I_{oi}$ is given by

$$N_o+B_o+\Sigma I_{oi} = N_o + [B_{oa} +B_{oa}/5] +\Sigma(F_{ci}F_{pi}/F_{bi})\, [B_{oa} + B_{oa}/5] \tag{44}$$

$$= N_o + 1.2B_{oa}\, [1+\Sigma(F_{ci}F_{pi}/F_{bi})]$$

Recall from Eq. (35) that B_{oa} equals MS/W_{DS} and E_b equals S/R_b. Then taking the margin issues into account which randomly reduce the power of the desired signal, the ratio $E_b/(N_o+B_o+\Sigma I_{oi})$ equals